New On-line Excitation-System Ground-Fault Location Method Tested in a 106 MVA Synchronous Generator

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I. Nomenclature

f	Network frequency
V	Grounding resistor voltage.
V_f	Field voltage.
V_{ph}	Phase voltage in the low-voltage side of the excitation transformer.
R_G	Grounding resistor.
R_F	Fault resistance.
$V_{ph,f}$	AC component of phase voltage in the low-voltage side of the excitation transformer.
$V_{AC,f}$	Fundamental frequency AC component of grounding resistor voltage.
$V_{AC,3f}$	Third harmonic AC component of grounding resistor voltage.
V_{DC}	DC component of grounding resistor voltage.
V_{fAC}	AC component of the excitation voltage.
V_{fDC}	DC component of the excitation voltage.
V_{DC0}	Max. value of V_{DC} at of the field winding (0%).
x (%)	Rotor winding position expressed in percent.

II. Introduction

THE excitation field circuit of synchronous generators is isolated during normal operating conditions. The field winding is exposed to mechanical and thermal stress cycles as a result of the rotation speed and the temperature increase [1].

In addition to the normal stress, the field winding can be exposed to abnormal mechanical or thermal stress because of the overspeeding, vibrations [2], excessive field currents, poor cooling or stator negative sequence currents, among (some) others. This may result in a breakdown of the insulation between the field winding and the rotor iron at the points where the stress has the highest value [3].

In synchronous generators of pumped storage power plants, the insulation failures occur more often [4]-[5] since they are operated generally from stopped to rated power operating condition in a short time. This causes that the temperature of the insulation alter very fast and frequently, increasing the possibility of an insulation failure.

As the excitation system is isolated, a single ground fault cause a negligible fault current, which and it does not represent any immediate danger. However, if a second ground fault occurs, high fault currents and severe mechanical unbalances may arise quickly and lead to serious damage [6]. In some cases the field current, flowing through the rotor iron, could generate enough heat to melt it [7]-[8]. It is essential, therefore, that the first insulation failure be detected [9]- [11], and the generator be removed from service in order to check the insulation [12].

Currently, the fault diagnosis is an active research field in induction motors [13] - [17], permanent magnet synchronous motors [18]-[20] and synchronous machines [21]-[22].

Regarding the synchronous generator, there are several techniques for detecting faults in rotor windings [23]-[28]. Some of these techniques are useful for ground fault detection, and they are based on AC or DC voltage injection [29]-[30]. Novel ground fault detection [31] and location [32] methods, without using voltage injection, have also been proposed recently for static excited generators.

This paper presents tests of a new on-line field-winding location method, performed in a 106 MVA synchronous machine of a storage pumped power plant.

Starting in May 2011, sporadic alarms of the rotor ground-fault protection went off in the plant under study. After a few months, the ground-fault rotor protection became trip commands. Numerous rotor ground-fault protection trips always occurred about hour after the synchronization to the network. However, after the protection trips, when the field winding insulation was checked, no failure was found. All the evidence seemed to indicate that the fault in the rotor was caused by the simultaneous effects of centrifugal forces and temperature, as

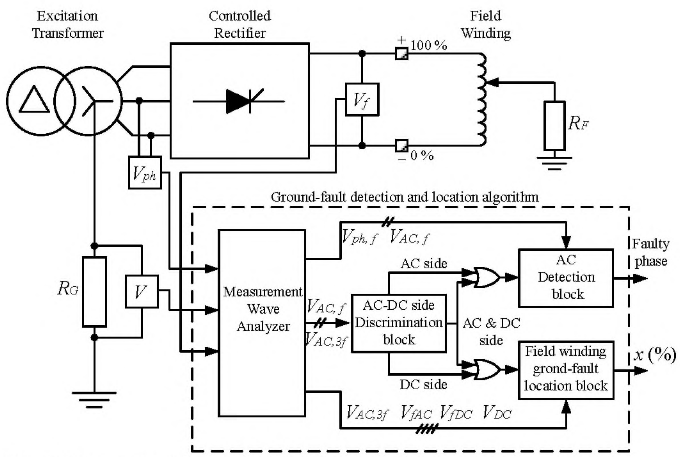

Fig. 1 Rotor ground fault detection system layout.

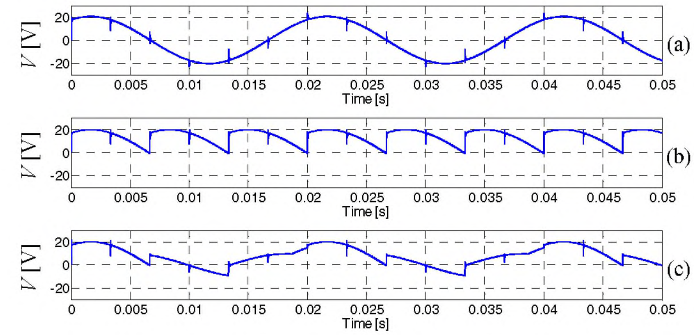

Fig. 3 Grounding resistor voltage (V) waveform during solid ground-fault test (R_F = 0Ω) in a 5kVA laboratory synchronous generator. (a) AC side ground fault; (b) DC side ground fault; (c) simultaneous AC and DC side ground fault.

the trip occurred an hour after the synchronization, and no evidence of defect was found when the machine was stopped. Because of these trips, a non-programmed extraction of the rotor was planned just for locating and repairing the fault. Through the application of this new detection method the ground fault was located.

In order to carry out this method, the neutral of the low voltage side of the excitation transformer was grounded through a high value resistor. The voltage registered at this grounding resistor was analysed following this novel fault location algorithm, and the ground fault was located in the AC side of the excitation system.

On the other hand, once the generator was repaired, the owner of the plant allowed authors to perform several intentional ground faults in the field winding, in order to test the accuracy of the method in the location of ground faults on the DC side.

III. Brief Description of the Rotor Ground Fault Location Method

Firstly this method allows discriminating whether the ground fault is in/on the AC side or on the DC side of the excitation system. In addition, if the fault is located in the DC side, it is possible to provide an estimation of the ground fault location along the field winding.

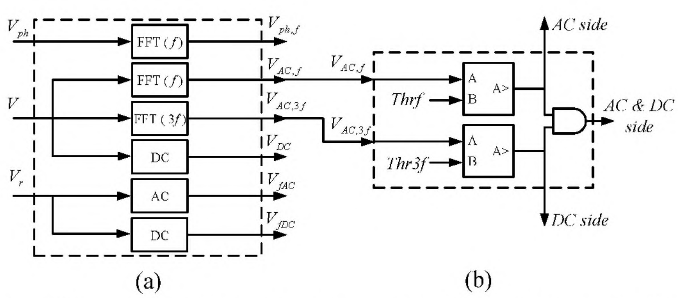

Fig. 2 Scheme of the Measurement Wave Analyzer block (a), and scheme of the AC-DC discrimination block (b).

As additional equipment, only a high value grounding resistor is required at the neutral of the excitation transformer low-voltage side. The grounding resistance value should be calculated in order to limit the ground-fault current to a very low value; in the experience described in this paper, the voltage between the neutral and ground, when the fault occurred, was almost 100 V and a 10 kΩ grounding resistor was utilized to limiting the fault current to 10 mA.

The waveform of the voltage measurement at the grounding resistor (V), in the field winding (V_f) are analysed to detect and locate the ground fault (Fig 1). In the Measurement Wave Analyzer block, the harmonic components of the voltage measurements, necessary for the algorithm, are obtained (Fig. 2 (a)).

A. AC/DC side discrimination

In the event of a ground fault in the excitation system, a current will flow through the grounding resistor and the frequency of the grounding resistor voltage (V) will depend on the position of the defect in the excitation circuit, AC side, DC side or both.The following faults may be identified:

a) AC side fault: the resistor grounding voltage amplitude depends on the fault resistance value. Moreover, it has the network frequency f (Fig. 3 (a)). This is a usual ground-fault detection technique used in AC distribution systems.

b) DC side fault: the wave amplitude depends on the fault resistance value and its frequency is three times the network frequency, $3{\cdot}f$ (Fig. 3 (b)). This frequency is caused by the ripple of the thyristor rectifier output voltage, as described in [31]-[32].

c) Simultaneous AC and DC side faults: the waveform has first and third order harmonic components (f and $3{\cdot}f$) (Fig. 3 (c)).

In conclusion, by the analysis of the frequency of the grounding resistor voltage, it is possible to differentiate whether the fault is in/ on the AC or in the DC side. In this way, the AC-DC Discrimination algorithm is based on the comparison of the fundamental and the third harmonic component to their own setting thresholds, *Thrf* and *Thr3f* (Fig. 2 (b)).

B. Field winding ground-fault location algorithm

There is also a DC component that appears in the voltage measurement of the grounding resistor in case of ground fault in the field winding.

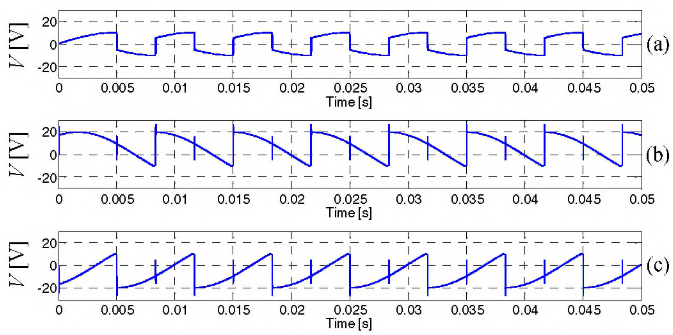

Fig. 4 Grounding resistor voltage waveform for different fault points at the field winding: a) 50%, b) 0% c) 100%, in a 5kVA laboratory synchronous generator (V_{fDC} = 20V, R_G = 5kΩ, R_F = 0Ω).

The principle behind the location method is the linear relationship between the DC voltage component in the grounding resistor (V_{DC}) and the position of the fault along the field winding (x (%)). The amplitude of V_{DC} is maximum with positive polarity, when the fault occurs in the negative terminal, which is considered as the start of the winding (0 %) (Fig. 1) as shown in Fig. 4 (b). On the other hand, if the fault occurs in the positive terminal, which is the end of the winding (100%), V_{DC} has the same amplitude, but the polarity is negative (Fig. 4 (c)). However, V_{DC} is zero for faults at the midpoint of the winding (50%), as shown in Fig. 4 (a).

According to [32], the maximum value of the DC component (V_{DC0}) depends on the value of the fault resistance R_F. Both parameters can be obtained through the expressions (1) and (2).

$$R_F = R_G \cdot \left(\frac{V_{fAC}}{V_{AC,3f}} - 1 \right) \tag{1}$$

$$V_{DC0} = \frac{|V_{fDC}|}{2} \cdot \left(\frac{R_G}{R_F + R_G} \right) \tag{2}$$

Expression (2) shows the linear relationship between the DC component of the field voltage (V_{fDC}) and the maximum value of V_{DC} (V_{DC0}).

In this way, just measuring V_{DC}, the position of the ground fault (x (%)) can be easily obtained using expression (3).

$$x(\%) = 50 \cdot \left(1 - \frac{V_{DC}}{V_{DC0}} \right) \tag{3}$$

The complete rotor fault location methodology is summarized in the scheme of the location block, shown in Fig. 5 (b).

In Fig. 6 as an example, V_{DC} is represented at different positions for several values of fault resistance, R_F in a laboratory 5 kVA synchronous machine, where V_{fDC} was adjusted to 20 V, and the grounding resistor R_G was set to 5 kΩ.

C. AC-side ground-fault detection algorithm

If the ground fault occurs in the AC side of the excitation system, the fault current depends on the fault resistance value. The value of the fault resistance of AC-side ground fault can be obtained by using the expression (4):

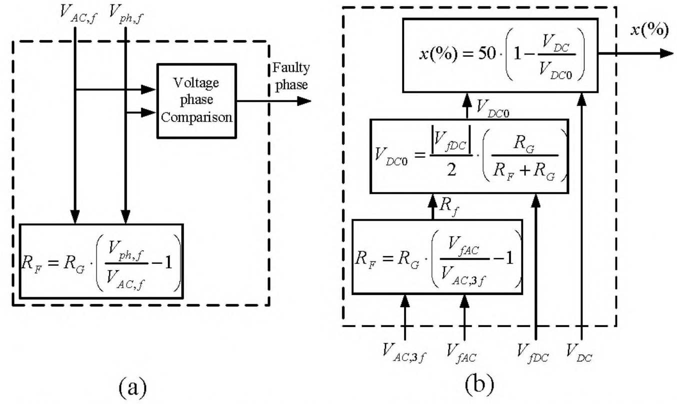

Fig. 5 Scheme of the Field winding ground fault-location block (a), and scheme of the AC-side Detection block (b).

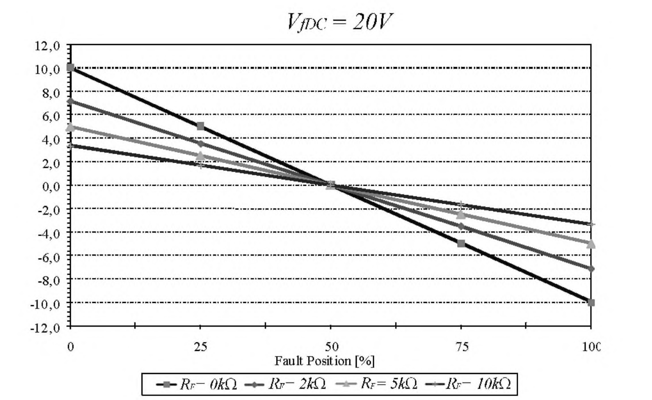

Fig. 6 V_{DC} and Fault-position for different R_f in a 5kVA laboratory synchronous machine.

$$R_F = R_G \cdot \left(\frac{V_{ph,f}}{V_{AC,f}} - 1 \right) \tag{4}$$

Moreover, the faulty phase is determined by the phase angle comparison between $V_{ph,f}$ and $V_{AC,f}$. The algorithm for detecting ground faults in the AC side of the excitation system is summarized in Fig. 5 (a).

IV. 106 MVA Synchronous Machine & Power Plant Description

The 106 MVA synchronous machine is in a four unit storage pumped power plant. It is coupled to an 85 MW pump-turbine, so, it can rotate in both directions, in generator or pump mode. The starting in pump mode is performed through a wound rotor asynchronous motor. Further data are included in the Appendix, Table III and Table IV.

The first commissioning took place in 1982 and the last major overhaul was in 2004.

The generator rotor ground-fault protection system is based on an R/C balance bridge [5]. The bridge consists of two resistors (R_1 and R_2) and three capacitors (C_1, C_2 and C_x), see Fig. 7.

To balance the bridge the capacitor Cx should be adjusted, so the voltage across the two resistors is null. In the event of rotor ground fault, the fault resistance shunts the capacitance of

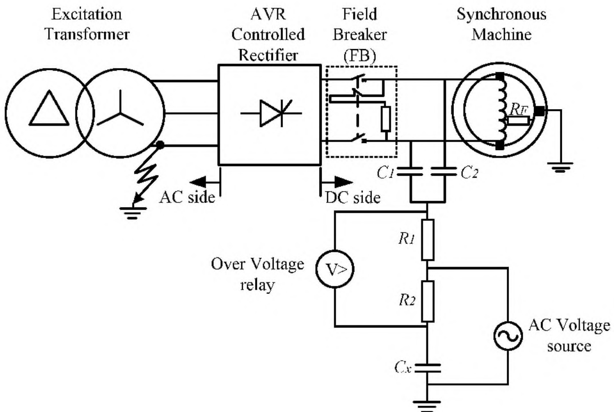

Fig. 7 Simplified rotor ground-fault protection scheme.

the rotor winding and disturbs the balance of the bridge. The voltage difference across the two resistors is applied to the overvoltage relay. The voltage applied depends on the fault resistance R_F. The setting on the protection is the equivalent voltage for detecting a fault resistance value lower than 2.6 kΩ and the operating time is 1s. Finally, in the aforementioned figure, an important fact can be observed: If there is a ground fault in the AC-side of the excitation system, the rotor ground-fault protection system will detect the unbalances caused by the fault when the field breaker (FB) is closed (Fig. 7). But when the protection commands the opening of the FB, the AC fault is not detected.

From October 2011 numerous rotor ground-fault protection trips took place always about an hour after the synchronization to the network. However, after the protection trips, when the field winding insulation was checked, no failure was found. The rotor insulation was 800 MΩ, testing at $1000V_{dc}$, while the rotor ground-fault protection setting was 2.6 kΩ. The rotor protection relay was also tested and no evidences of wrong operation were found.

All the data seemed to indicate that the fault in the rotor was due to the effect of centrifugal forces and temperature simultaneously. As the fault disappeared when the machine was stopped, centrifugal force should be one of the causes of the fault. Furthermore, the temperature reached in the field winding seemed to have influence as well, because the fault occurred always about an hour of operation after the synchronization.

Despite this generator had a major overhaul six years before, a non-programmed extraction of the rotor was planned just for locating and repairing the fault. This process is very costly in money and time, about 250 k€ and 6 weeks respectively.

V. Field Tests Performed for the Location of the Ground Fault in the AC-Side

This section includes the field tests performed in the power plant during the synchronous machine operation, and posterior analysis in order to detect and locate the ground fault in the AC-side. In Fig. 8, the set-up of the field test in the power plant is shown.

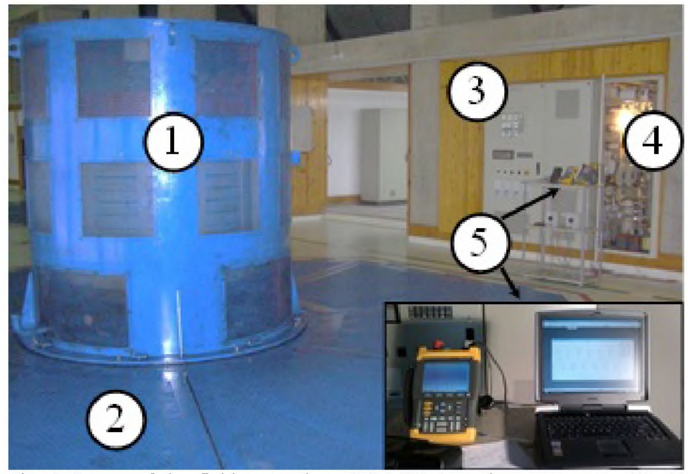

Fig. 8 Set-up of the field test, where 5.5 MW Asynchronous motor (1), 106 MVA Generator (2), Automatic Voltage Regulator (Unitrol F) (3), Field Breaker (4) and additional equipment for field measurements (5).

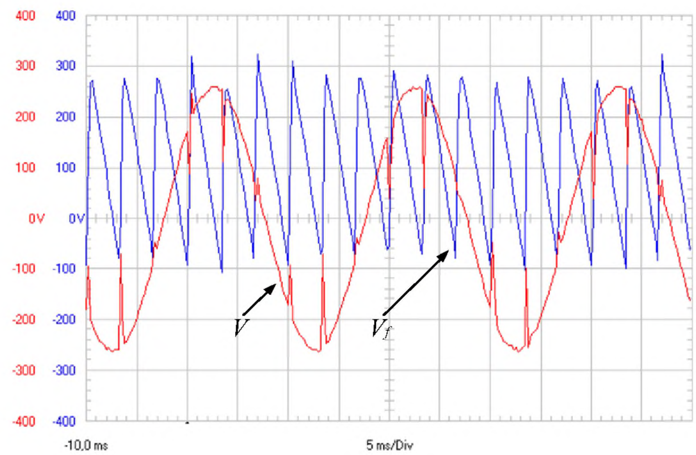

Fig. 9 Waveform of the voltage measurement at the grounding resistor (V) and at the field winding (V_f) during field tests.

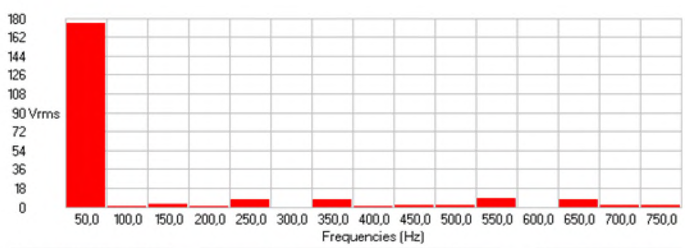

Fig. 10 FFT analysis of the voltage measurement at the grounding resistor (V).

The rotor ground fault output relay was disconnected in order to avoid the machine stop. After the rotor ground fault relay tripped the capacitor C_1 and C_2 were disconnected (Fig. 7) and the grounding resistor at the low-voltage side of the excitation transformer was connected. In this condition the voltage in the grounding resistor (V) and in the field winding (V_f) were registered (Fig. 9), and the FFT was performed to V (Fig. 10).

The voltage measured in the grounding resistor had only 50 Hz AC component. All the measurements are summarized in Table I.

According to the AC/DC side discrimination criteria, there was

Fig. 11 Ground-fault located at the AC side of the excitation system circuit.

TABLE I
FIELD TEST RESULTS FOR AC-SIDE GROUND FAULT TRIP

$V_{ph,f}$	AC component of phase voltage of excitation transformer low-voltage side at f	181.0 V
$V_{AC,f}$	AC component of grounding resistor voltage f	179.0 V
$V_{AC,3f}$	AC component of grounding resistor voltage $3{\cdot}f$	3.0 V
V_{DC}	DC component of grounding resistor voltage	0.4 V
f	Fundamental frequency	50 Hz
V_{fDC}	DC component of the excitation voltage	110.0 V
V_{fAC}	AC component of the excitation voltage	96.0 V

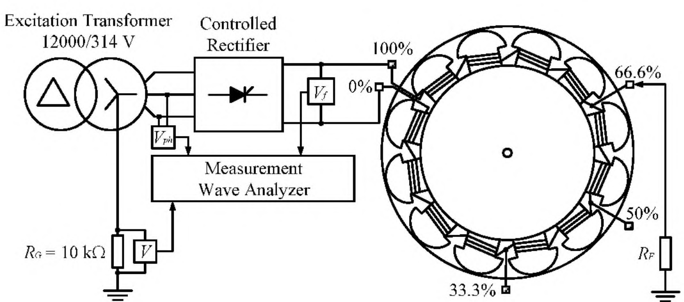

Fig. 12 Simplified scheme of the experimental setup for the test of ground-fault location in the field winding (DC side)

a fault in the AC side of the excitation system, as the frequency of the voltage measured under faulty condition was 50 Hz.

Finally, the fault resistance value, obtained by expression (4), was 117.3 Ω at the instant of the voltage measurement in Fig. 9, although in different tests performed the same day, the fault resistance value was even lower.

After checking the insulation of the excitation transformer, thyristor bridges and the connection cables, the ground fault was found in one of the six cables between the excitation transformer and the rectifier (Fig. 11).

We can conclude that the AC/DC discrimination criterion is suitable not only for laboratory scale machines, but also for large commercial machines.

The insulation failure in the cable did not produce a direct ground fault in cold condition, as the insulation was above the 2.6 kΩ. As the cable temperature increased, the insulation decreased until the insulation level was low enough, and it caused the protection trip.

On the other hand, when the machine was tripped, the field breaker (FB) opened and the AC side of the excitation system (Fig. 7), where the fault was placed, was isolated from the rotor ground fault relay. This was the reason because the trip of the rotor ground-fault protection disappeared after the trip..

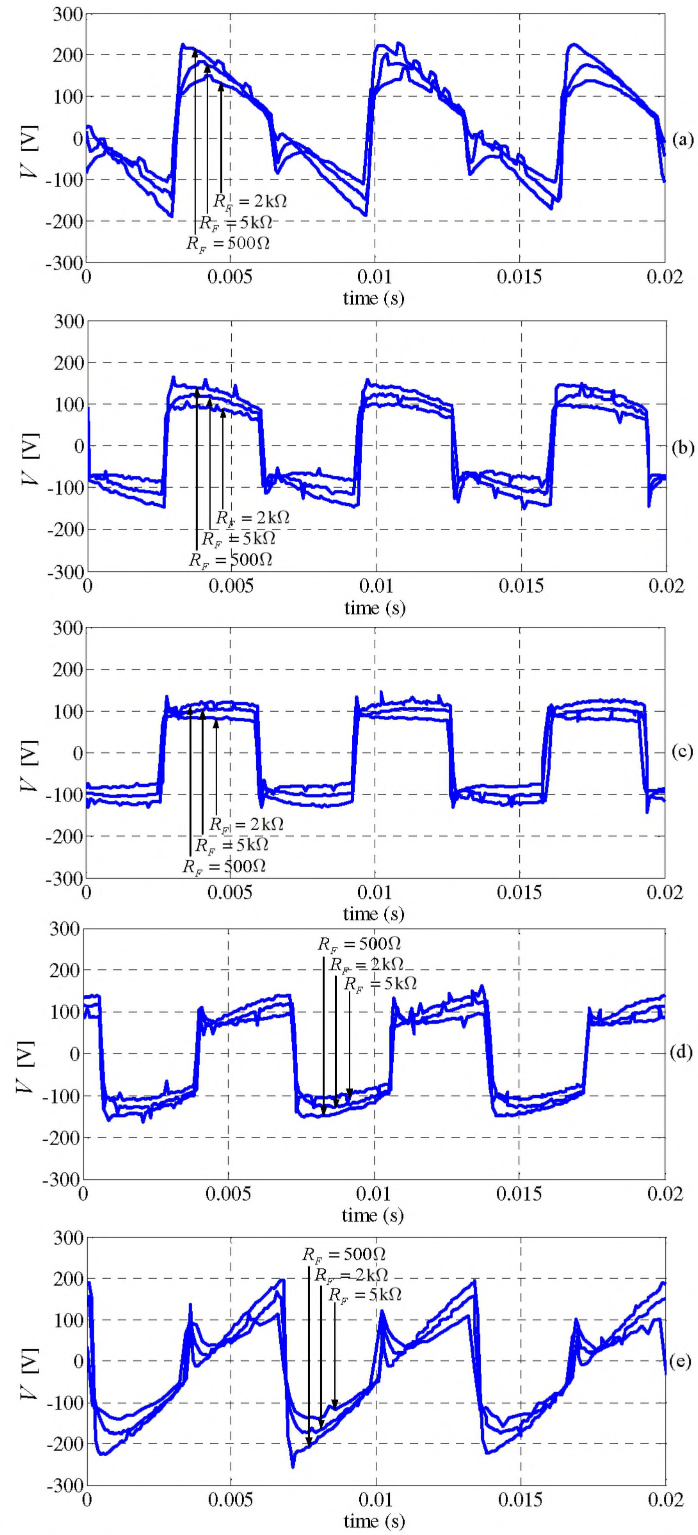

Fig. 13 Waveform of the voltage measurement at the grounding resistor (V) during ground fault, with different fault resistance values, at: (a) 0%; (b) 33.3%; (c) 50%; (d) 66.6%; (e) 100%;

VI. ADDITIONAL FIELD TESTS PERFORMED FOR THE LOCATION OF INTENTIONAL FAULTS IN THE FIELD WINDING (DC-SIDE)

Thereafter, the owner of the power plant let the authors to test the location method in order to locate ground faults in the field winding. These faults were intentionally made through the installation of a fault resistance (R_F) between the inter-pole

TABLE II
FIELD TEST RESULTS FOR DC-SIDE GROUND FAULT

R_F (Ω)	V_{fDC} (V)	V_{DC} (V)	V_{fAC} (V)	$V_{AC,3f}$(V)	x (%)	E (%)
Negative Terminal (x = 0%)						
500	51	23	135	132	3,2	3,2
2000	51	22	134	111	-2,1	-2,1
5000	47	15	133	93	3,5	3,5
Negative Terminal (x = 33.3%)						
R_F (Ω)	V_{fDC} (V)	V_{DC} (V)	V_{fAC} (V)	$V_{AC,3f}$(V)	x (%)	E (%)
500	45	7	134	118	32,3	-0,7
2000	49	7	135	98	31,2	-1,8
5000	50	6	135	81	30,7	-2,3
Negative Terminal (x = 50%)						
R_F (Ω)	V_{fDC} (V)	V_{DC} (V)	V_{fAC} (V)	$V_{AC,3f}$(V)	x (%)	E (%)
500	50	-1	135	115	51,4	1,4
2000	47	-1	133	97	52,0	2,0
5000	45	-1	134	82	53,3	3,3
Negative Terminal (x = 66.6%)						
R_F (Ω)	V_{fDC} (V)	V_{DC} (V)	V_{fAC} (V)	$V_{AC,3f}$(V)	x (%)	E (%)
500	50	-10	136	120	72,7	6,7
2000	46	-8	134	94	74,8	8,8
5000	49	-7	136	89	71,8	5,8
Positive Terminal (x = 100%)						
R_F (Ω)	V_{fDC} (V)	V_{DC} (V)	V_{fAC} (V)	$V_{AC,3f}$(V)	x (%)	E (%)
500	48	-26	134	135	103,8	3,8
2000	49	-24	134	111	109,1	9,1
5000	49	-18	128	91	101,7	1,7

connections and ground (shaft of the generator), see Fig. 12. The waveforms of the voltage at the grounding resistor (V), for several values of fault resistance, are shown in Fig. 13. As observed the waveforms are symmetrical to the midpoint of the field winding (50%) (Fig. 13(c)). Therefore, the waveforms of V in case of ground fault at 0% (Fig. 13(a)) and at the 100% (Fig. 13(e)) are symmetrical, but with reverse polarity. The same idea can be observed if comparing the waveforms of V in case of fault at 33.3% (Fig. 13(b)) and at 66.6% (Fig. 13(d)). In every mentioned case, the third-harmonic component of V is equal (for a fixed value of R_F), but the DC component has different amplitude. As described previously, this DC component has positive polarity in case of the defect in the range 0-50% of the field winding, and negative polarity in the range 50-100%. In case of ground fault in the midpoint (Fig. 13(c)), the third-harmonic component is the same as in the previous cases, but the DC component is very close to zero.

The described conclusions can be checked in Table II, where the values of the variables measured in the test are summarized. In this table, x (%) is the location of the ground fault obtained through this new method, and E is the error of location, expressed in %.

As observed in this table, as the fault-resistance value increases, the value of V_{DC} and $V_{AC,3f}$ decreases. The results of these tests show that the accuracy of the location of the ground fault is acceptable for any point of the field winding, even for higher values of R_F (R_F = 5kΩ). The errors in the location remain under 9.1% in every case.

VII. CONCLUSIONS

The results of the application of a new ground-fault location method in a 106 MVA synchronous machine have been presented. The tests present good results not only in the detection of a real fault placed in the AC-side, but also in the location of faults along the field winding, tested by intentional ground faults.

In a 106 MVA synchronous machine one of a pumped storage power plant, the rotor ground-fault protection tripped about one hour after the synchronization and the trip disappeared when the machine was stopped. All the evidences pointed to a fault in the field winding due to the effect of centrifugal forces and temperature.

However, by the use this novel method, the default was unexpectedly found in a cable between the excitation transformer and the rectifier. The insulation of the cable was damaged by the vibration of the generator breaker when operates, and, at high temperature, the insulation resistance was so low that the rotor ground fault relay tripped.

One of the main conclusions of this work is that the AC/DC side discrimination criterion worked properly in a large commercial synchronous generator. This discrimination method can be determinant, taking into account that the ground faults in the AC-side of the excitation system can be very difficult to locate, since this defect is not detected by the conventional protection system when the field breaker is opened.

In addition, once the generating unit was repaired, several intentional ground-faults were performed in the field winding, in order to test accuracy of this new location method in the DC side. The results show satisfactory accuracy of this method (errors lower than 9.1%) at every point of the field winding, and with different values of fault resistance.

VIII. APPENDIX

TABLE III
CHARACTERISTICS OF SYNCHRONOUS MACHINE

Rated apparent power	106	MVA
Rated Power Factor	0.8	
Rated voltage (± 5,0%)	12	kV
Frequency	50	Hz
Rated speed	500	rpm
Direct-axis synchronous reactance (unsat) X_d	1.05	pu
Quadrature-axis synchronous reactance X_q	0.70	pu
Direct-axis subtransient reactance (unsat) X'_d	0.26	pu
Direct-axis subtransient reactance (unsat) X''_d	0.19	pu
Quadrature-axis subtransient reactance X''_q	0.19	pu
Direct-axis transient open-circuit time constant T'_{do}	9.5	s
Direct-axis transient short-circuit time constant T'_d	1.6	s
Direct-axis subtransient short-circuit time const T''_d	32	ms
Rated field current I_{fn}	1060	A
Rated field voltage U_{fn}	241	V

TABLE IV
SYNCHRONOUS GENERATOR STATIC EXCITATION SYSTEM TECHNICAL DATA

Excitation transformer	
Winding connection	Dy5
Ratio	12 kV ± 2.5%/0.314 kV
Rated power	630 kVA
Thyristor bridge	
Operation mode	Fully controlled
Maximum output voltage	397 V
Minimum firing angle	15 º